Seasonal trends of indoor fine particulate matter and its determinants in urban residences in Nanjing, China

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A B S T R A C T

Most people spend more than 80% of their time indoors; thus, indoor air pollution has a significant influence on an individual's exposure to air pollution. In this study, PM2.5 concentrations in both indoor and outdoor air were simultaneously measured in urban residences in Nanjing, China. The measurements were carried out using MicroPEM personal exposure monitors during summer, winter and transition seasons from March 2016 to February 2017. Information on building characteristics, occupants' activities and socioeconomic status (SES) variables was obtained through questionnaires during the sampling period. Significant seasonal variations in indoor and outdoor PM2.5 levels were observed in this study, with the highest PM2.5 concentration in winter and the lowest in summer. The correlation between indoor and outdoor PM2.5 concentrations in transition seasons was higher than that in winter and summer. Linear regression models were fitted to log-transformed indoor PM2.5 concentrations to determine potential influencing factors. Outdoor PM2.5 was found to be the major source of residential indoor PM2.5 pollution. The household activity of cooking was an indoor determinant of PM2.5 concentrations in homes with open-plan kitchens or when the kitchen door was open during cooking. More frequent building ventilation could increase indoor exposure to outdoor PM2.5 in transition seasons and winter or when the outdoor air quality is poor. SES variables such as dwelling ownership and household income were associated with indoor PM2.5 concentrations.

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1. Introduction

Fine particulate matter with an aerodynamic diameter less than 2.5 μm (PM2.5) has become the primary air pollutant in most Chinese cities [1]. Exposure to PM2.5 is associated with negative health effects, such as cardiovascular and respiratory diseases, cancer and preterm birth [2–4]. Although the air quality in China has been improving in recent years, PM2.5 still ranks 5th among all risk factors for disability-adjusted life-years (DALYs) in China [5]. Only 19% of the population in China live in areas that meet the annual PM2.5 standard metric of the National Ambient Air Quality Standards (NAAQS) [6]. In a recent study, it was estimated that PM2.5 pollution contributed to 15.5% (1.7 million) of all deaths in China in 2015 [7].

Ambient PM2.5 concentrations are usually used for PM2.5 exposure assessment in epidemiological studies [8–10]. However, most people spend more than 80% of their time indoors [11–13]. Therefore, the indoor PM2.5 pollution level has a significant influence on human exposure to air pollution. The difference between indoor and outdoor PM2.5 concentrations has become a source of measurement bias in epidemiological studies [14,15]. Some researchers discovered that the geographical heterogeneity in PM-related mortality observed in air pollution and health effects studies can be partially explained by the regional difference of indoor exposure to outdoor PM in the United States [16], Europe [17] and China [18]. Understanding the relationship between indoor and outdoor air pollution is essential to better characterize ambient...
PM$_{2.5}$ exposure and health effects.

Indoor PM$_{2.5}$ pollution can arise from various sources both outdoors (e.g., vehicles, industry, heating emissions and atmospheric chemical reactions) and indoors (e.g., cooking, cleaning and dusting) [19]. Various studies have explored the relationship between indoor and outdoor PM$_{2.5}$ concentrations in urban areas in China, including Beijing [20,21], Tianjin [22], Nanjing [23] and Hong Kong [24], in a single season. Cao et al. [25] found that the indoor-outdoor relationship for PM$_{2.5}$ and its chemical components were different in summer and winter. Qi et al. [26] established two indoor PM$_{2.5}$ prediction models based on ambient data and discovered that the lagging effect of outdoor pollution on indoor levels was different in heating and non-heating seasons. The determinants of indoor PM$_{2.5}$ concentrations were related to the season [27]. However, to the best of our knowledge, few studies have been conducted to examine the determinants of seasonal indoor PM$_{2.5}$ pollution in China. According to the Exposure Factors Handbook of Chinese Population (Adults) [13], the indoor ventilation time is markedly different in summer, winter, and transition seasons (i.e., spring and fall). Ambient air pollution usually shows obvious seasonal variations in China [28]. The seasonal trends of outdoor PM$_{2.5}$ pollution and indoor ventilation frequency may influence the infiltration of outdoor PM$_{2.5}$ [29,30] and the diffusion of indoor PM$_{2.5}$ emitted by indoor sources [31].

In this study, we focus on the seasonal trends of indoor PM$_{2.5}$ concentrations and explore its determinants in urban residences in Nanjing. Nanjing is located in the western region of the Yangtze River Delta (YRD) and is one of the most developed and rapidly urbanized areas of China. However, the air quality conditions are poor, especially PM$_{2.5}$ [32,33]. This study will shed light on the current status of indoor PM$_{2.5}$ pollution in urban residences and provide a better understanding of the seasonal indoor-outdoor relationship of PM$_{2.5}$, which is essential for the accurate exposure assessment of air pollution. Moreover, the results will be useful for improving indoor air quality in homes and for reducing human exposure to PM$_{2.5}$ by modifying individual behavior patterns indoors.

2. Methodology

2.1. Study area and sites

The study was conducted in Nanjing, a major city of the YRD, in East China (N 31°14′–32°37′, E 118°22′–119°14′). Homes participating in this study were recruited by telephone interview and door-to-door surveys. A preliminary survey was performed to determine the construction date of the residences during recruitment. Single-stage stratified sampling was used, in which the residences in Nanjing were stratified into four groups based on the construction date of the building (before 1990, 1991–2000, 2001–2010 and after 2011). After informing the occupants of the objective of our research, 60 families joined this study. Among the 60 residences, 9 were built before 1990, 12 between 1991 and 2000, 14 between 2001 and 2010, and 25 after 2011. Apartment buildings were the main residence type in this study. Informed consent was obtained from each participant. The homes were randomly distributed in 8 urban districts in Nanjing: 20 in Xuanwu, 4 in Qinhuai, 2 in Gulou, 14 in Jianye, 6 in Qixia, 3 in Yuhuatai, 7 in Pukou, and 4 in Jiangning (Fig. 1).

2.2. Indoor and outdoor PM$_{2.5}$ monitoring

Nanjing has a subtropical and humid climate with a cold winter and hot summer. In transition seasons (i.e., spring and fall), the average temperature is comfortable, ranges from 15.7 °C to 23.6 °C [34]. Generally, air conditioning is not used in transition seasons [35], and people often ventilate by opening windows. Indoor ventilation times are similar in the transition seasons (i.e., spring and fall) in China, according to the Exposure Factors Handbook of Chinese Population (Adults) [13]. When windows are opened, outdoor-originating particles contribute more than 90% of the indoor PM$_{2.5}$ concentration [19]. Thus, the sampling period in this study was divided into three seasons: summer (June–August 2016), winter (December 2016–February 2017), and transition seasons (March–May/October–November 2016). Out of the 60 residences in this study, only 16 families participated across multiple season treatments. The families that dropped out were supplemented by newly recruited homes each season. Finally, 35 families were sampled in summer, 36 in winter, and 39 in transition seasons. It should be noted that a proportion of the dataset consists of non-independent data (i.e., observations from families that were sampled repeatedly across multiple seasons), which may have slightly inflated the Type I (false positive) error rate. The characteristics of the families in each season are given in Tables S1–S2. Indoor and outdoor PM$_{2.5}$ concentrations were measured simultaneously by micro personal exposure monitors (MicroPEM) (RTI International, Research Triangle Park, NC, USA), operated at a nominal flow rate of 0.5 L/min. The MicroPEMs were zeroed with an in-line high-efficiency particulate air (HEPA) filter and pre-calibrated with a TSI model 4143 mass flow meter (TSI, Inc., Shoreview, MN, USA) using the Docking Station software provided by RTI International. The indoor MicroPEMs were placed in the living room, approximately 1.5 m above the ground, away from open windows and doors. For outdoor sampling, the samples were located on the open balcony outside the home. When an open balcony was not available at the home, the samplers were set on the windows and an inlet top cap of the sampler was used to connect tubing for outdoor PM$_{2.5}$ sampling. When two or three adjoining families were selected, only one outdoor monitoring site was set outside the two or three homes. Forty-eight hour indoor and outdoor measurements were taken simultaneously in each home. The PTFE filters (25 mm, 3.0 μm pore size, Pall, Mexico) and batteries in the MicroPEMs were replaced by our researchers every 24 h.

The real-time PM$_{2.5}$ mass concentrations measured by the MicroPEMs were calibrated using the gravimetric mass concentrations retrieved from the filters in the samplers. The result of the regression analysis showed that the two types of PM$_{2.5}$ mass concentrations agreed well (R$^2$ = 0.86, p < 0.001) (Fig. S1). Therefore, the real-time PM$_{2.5}$ mass concentrations presented in this paper have not been corrected to their gravimetric equivalent.

2.3. Questionnaires

A questionnaire with information on housing characteristics and SES was completed at each home (shown in the Supporting Information), including building height, construction date, floor area, building orientation, distance to the main traffic road, recent refurbishment, new furniture purchases, dwelling ownership, number of occupants, pet ownership, and household monthly income. Additionally, participants were asked to complete a time-activity questionnaire to obtain information on activities that would influence the indoor PM$_{2.5}$ level in their home during the sampling period, including opening living room windows, cooking, smoking indoors, and the use of air conditioners and air cleaners.

2.4. Data analysis

Descriptive statistical analyses were conducted for the indoor and outdoor PM$_{2.5}$ mass concentrations and possible indoor PM determinants. The Kruskal-Wallis H test was performed to compare